Understanding Digital Modulation

Digital modulation is the key to today s high speed data transfers and has made possible such developments as high-speed digital modems and even HDTV.

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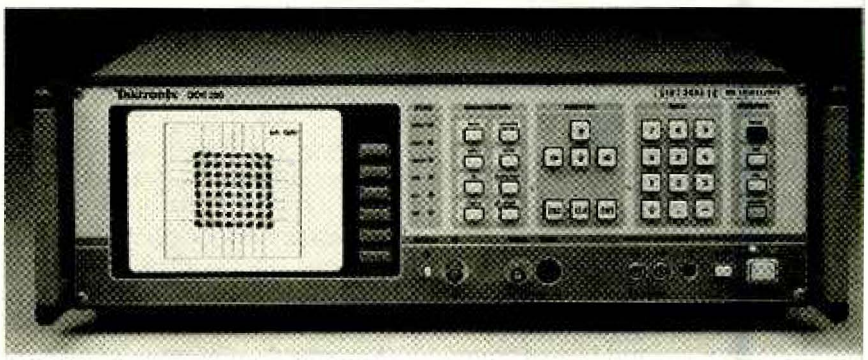

Analog modulation techniques have served us well for many decades, and have been the mainstay of radio and TV broadcasts, as well as ham and mobile communications. The two basic analog-modulation methods are Amplitude Modulation, or AM (both as double and single sideband) and Frequency Modulation or FM. With the advent of computers and the widespread use of digital communications, neither AM nor FM has proved to be the best modulation choice as neither of those analog modulation schemes are efficient from the bandwidth vs. baud rate point of view. Therefore digital modulation techniques are required.

As most of course know, modulation is the process of encoding information onto a carrier signal. Since the carrier remains analog, the term "digital modulation" is a bit misleading. In digital modulation what is happening is that a carrier is modulated in discrete increments instead of the continuous envelope of conventional analog modulation methods. Each increment is then assigned a value of a bit or group of bits.

Before we go on, it is interesting to note that digital modulation techniques are not new by a long shot. The earliest wireless communications used Morse code, which is in essence digital modulation. The dots and dashes that comprise the code are basically the short and long pulses of RTZ-encoded digital data. During the earliest days of personal computers, hackers would build Morse-keyers, where the text would be typed on the computer screen, and the computer would toggle a relay to simulate the keying. Morse code is bandwidth-efficient, and although slow and a little dated, it still remains useful to this day.

ASK and FSK. Morse code-modulated signals would be known today as Amplitude Shift Keying or ASK. With ASK, the carrier is keyed between two discrete levels. Although any two carrier values could be used, for maximum efficiency these levels are keyed between full carrier and no carrier. This can be seen in Fig. 1, where ASK is shown in the middle trace and the modulating (digital) signal is shown at the top trace.

ASK suffers from very poor noise immunity during the period where the carrier is off. Therefore, it is not the modulation of choice for fast or critical transmissions. However, ASK consumes transmitter power only during the period the carrier is actually keyed on, and the transmitter design itself is uncomplicated. Thus, it is widely used for simple battery-powered devices, such as garage-door openers.

With Frequency Shift Keying or FSK, the carrier is always on, as shown in bottom trace of Fig. 1. In that sample trace, the frequency shifts have been exaggerated for the sake of clarity.

FSK is a much more robust modulation method, as it has superior noise immunity. Receivers incorporate a limiter circuit much like FM detectors do, thus removing most, if not all, amplitude disturbances. Due to its robust receiving characteristics, the FSK modulation technique was frequently used in early modems.

The pitfall with FSK is that it occupies quite a lot of bandwidth for the amount of data-per-unit of time that it transmits. Bandwidth is a scarce commodity, and the need to transmit ever increasing data rates seems to be ever increasing. In order to minimize the occupied bandwidth, the frequency shifts are

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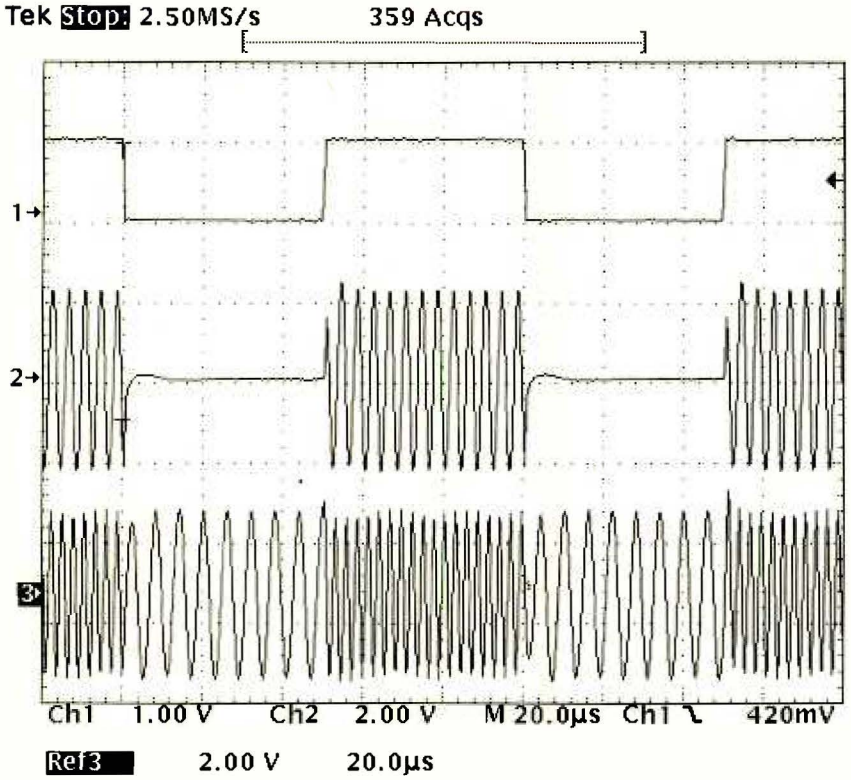

Fig. 1. ASK modulation (middle trace) and FSK modulation (bottom trace) are shown here. The top trace is the modulating signal.

kept as narrow as possible. Engineers soon realized that as the frequency shifts became narrower and narrower, they would look more like instantaneous phase shifts. Thus, Phase Shift Keying (PSK) was born; and its several variants, which allow extraordinary data rates to be transmitted, have largely superseded FSK.

Enter PSK. Phase Shift Keying was the next logical development, and it is what has allowed today's high-speed modems. In PSK, the carrier is subjected to abrupt phase changes as the modulation varies. This is shown in Fig. 2. Note that in the figure, the phase shift is a full 180 degrees, but the horizontal scale has been expanded with regard to the scale used in Fig. 1 to allow the modulation to be clearer.

PSK is difficult to view on traditional scope displays and even much more difficult to measure accurately. To get a better look at it, we need a better way to represent it—polar coordinates on a vector diagram. Such a diagram allows us to more easily see the relative phase shift of the waveform with respect to a phase reference. This is clearly seen in Fig. 3, where the horizontal dividing line is the in-phase axis, and the vertical dividing line is the quadrature axis. The dots in the horizontal axis represent the two possible states; in this example, no phase shift would indicate a logic "0" and a 180-degree shift would indicate a logic "1".

It did not take very long for engineers to realize that there is plenty of empty space between zero and 180 degrees. Would it be possible to modulate both the in-phase axis and the quadrature axis in varying amounts and obtain a vector with smaller phase shifts—say 90 degrees, or even lower, perhaps to 45 degrees?

An example of the latter case is shown in Fig. 4. This modulation method in the figure is known as Quadrature Phase-Shift Keying or QPSK. Each discrete state is known as a symbol, and since there are 8 different states, that means that each symbol is capable of carrying three bits. Thus, QPSK allows dramatic increases in the baud rate without substantially increasing bandwidth.

The phase shifts could be further reduced to obtain additional symbols, but again we run into trouble since all modulated data suffers from certain limitations. Although PSK is relatively immune from amplitude noise, phase modulated signals suffer from phase uncertainties called *jitter*. The jitter might be produced at either the transmitting or receiving ends, or caused by the medium used to send the signal. Thus, as the number of symbols increases, it becomes more difficult to accurately resolve the ever decreasing phase shifts. Additional sophistication and improvements are required to achieve higher modulation densities.

Marrying Phase and Amplitude. Further improvements upon the basic phase shifting might be possible. For instance, ASK modulation requires keying the amplitude between two states, but the only reason that one of those states traditionally has been fully off was to conserve transmitter power. Without such a requirement, amplitude modulation could take the form of several discrete levels, each one providing additional symbols. Engineers have found a way to happily marry multi-level ASK and QPSK, and thus provide a waveform with simultaneous amplitude and phase shifts where a very dense modulation (with many symbols) could be achieved.

This modulation method is known as Quadrature Amplitude Modulation, or QAM-xx, where the "xx" are the number of symbols supported by the modulation. That means that the example shown in Fig 5. is QAM-16. In this instance, each different state carries four different bits of information.

QAM is not limited to 16 symbols. Certain applications use QAM-64 and more. As the number of states increase, the symbols resemble twinkling stars when viewed in appropriate equipment, and thus people have nicknamed such displays as "constellation diagrams." Specially equipped oscilloscopes or spectrum analyzers, or dedicated digital communications equipment such as the unit shown in the beginning of this article are

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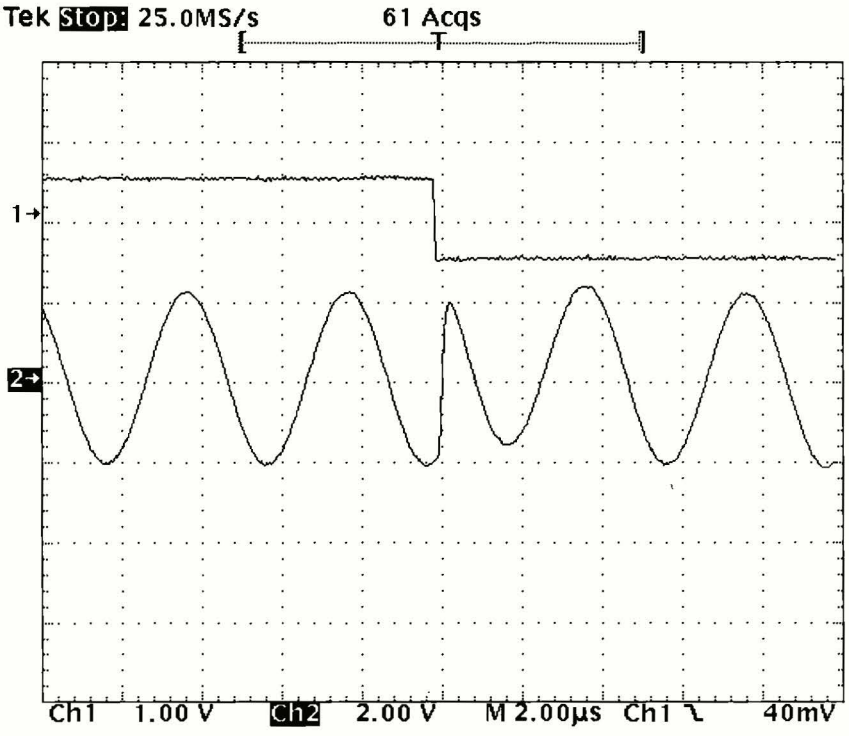

Fig. 2. An example of PSK modulation. Note the much shorter horizontal time scale as compared to Fig. 1.

required to view these diagrams.

Constellation diagrams clearly indicate the boundaries for which the symbols may be detected correctly. This is necessary since QAM is not perfect and suffers from jitter and amplitude uncertainties. The ideal dots may become wide, fuzzy blobs in actual operating conditions. Then some symbols may overlap with each other, and errors will occur. Those uncertainties limit the amount and density of symbols that may be reliably sent. Thus many modulation methods will fall back to a lower rate if excessive errors at the higher rates are detected. In addition, sophisticated error-correcting algorithms allow high-speed data to be effectively recovered. But those are topics beyond the scope of this short article.

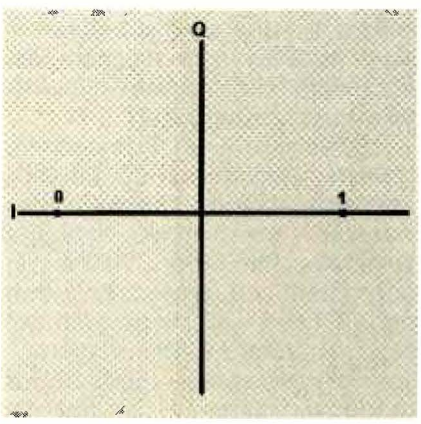

Fig. 3. Using both a vector diagram and polar coordinates makes it easier to examine PSK modulation.

High Definition TV and Beyond. With its very high baud rate, QAM has pushed digital modulation into the mainstream, allowing a variety of devices to become feasible. Digital video broadcasts, the dramatic speed increases of PC modems, and other improvements have been made possible by this technique.

This does not mean that QAM's supremacy is unchallenged. The FCC's Advisory Committee on Advanced Television Service evaluated a vestigial sideband (VSB) digital transmission system that had been developed for terrestrial, MMDS, and cable television broadcasting by the Zenith Electronics Corp. After extensive field tests and a long debate among the members of the Grand Alliance (a consortium of several corporations and the MIT), the system was adopted as the new high-definition, digital terrestrial standard for the United States. This finally occurred on December 1996. Among the reasons cited for the adoption was that VSB is more robust than QAM with regards to fading and that it provides faster recovery from dropouts, since VSB will still maintain receiver synchronization even if the received data is in error. Synchronization is extremely important, as all modern digital modulation methods use extensive error-correction algorithms, and these require at least data-clock synchronization.

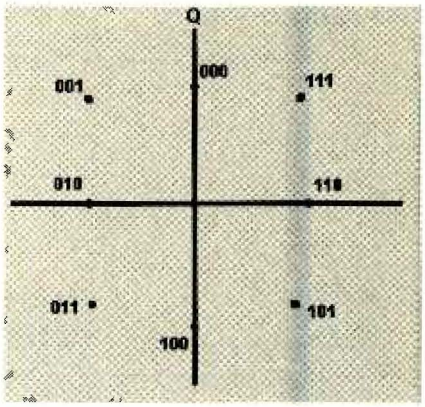

Fig. 4. The symbol positions in actual QPSK modulation may differ from the sample shown here.

QAM is a self-clocked modulation, and data dropouts will wipe the error-corrector's capability to recover. VSB, on the other hand, uses supplementary synchronization, which allows the receiver to rapidly recover after a data loss.

Just as with QAM, there are several variants for VSB, depending on the required data rates and robustness. Recommended modes are 8-VSB for terrestrial broadcasting, and 16-VSB for cable systems, although there is flexibility to accommodate other modes. Those modes allow one HDTV channel for the former, and two HDTV channels for the latter, to be transmitted within the 6 MHz bandwidth currently allotted to existing NTSC channels. The maximum data rate under optimum conditions for 8-VSB signal is 19.39 Mbps and twice that much for 16-VSB.

This is not to say that VSB has completely won the HDTV battle. Japanese and European consortiums are holding steadfastly to the newer OFDM (Orthogonal Frequency Division Multiplexing) modulation, which requires a lot of

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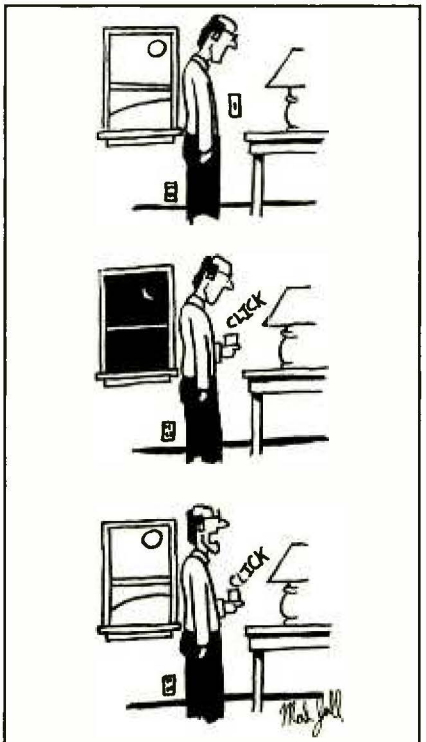
sound level.

The Balanced-Line Converter makes an excellent headphone amplifier. To use it as such, make an adapter cable from two female XLR connectors and a stereo phone jack. From the phone jack, the ground connection goes to pin 1 of one XLR connector, the ring connection to pin 2 of the same XLR, and the tip connection to pin 2 of the other XLR. For best results, the headphone impedance should be at least 32 ohms. Lower impedance headphones will produce less volume and distort when you turn the sound level up.

One word of warning: turning the Balanced-Line Converter on or off while it is connected to an amplifier or mixer console will produce a loud thump in the speaker system. One way to avoid possible speaker damage is to power up the amplifier/console and the Balanced-Line Converter at the same time through a switched outlet strip. Otherwise, power up the Balanced-Line Converter before the amplifier or console, and power it down after the amplifier/console is turned off. If that is not possible, you should turn the amplifier or console level controls to zero before switching power to the Line Converter. Ω



"Honey...What's this switch do?"

DIGITAL MODULATION

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computer power to implement—so much, in fact, that until recently there were no cost-effective digital processors powerful enough to implement the OFDM demodulator on a consumer product.

OFDM uses hundreds or even thousands of quadrature-modulated carriers, each transmitting at a low data rate. The parallelism of those carriers allow for the extremely high data rate required for HDTV applications.

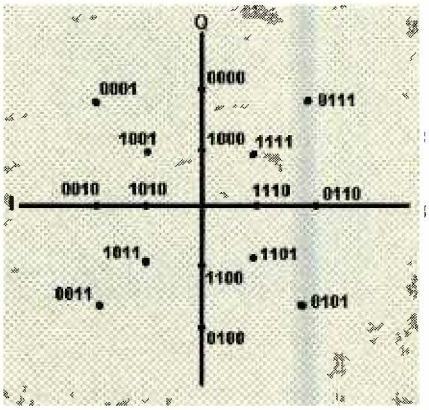

Fig. 5. This constellation diagram shows a QAM-16 signal—a quadrature-amplitude modulated carrier with 16 states or symbols.

Each digital-modulation system has, of course, its technical advantages and pitfalls. The advocates for each camp remain stubborn in their attempt to prove that their system provides the best solution. Even here in the US, there are uncertainties for VSB. Cable operators that have already committed to digital programming have done so by deploying QAM systems. They maintain that since a cable system does not suffer from multipath, fading, or other off-air disturbances, QAM is as robust as VSB in this application. Perhaps a better explanation would be that they are extremely reluctant to replace the very substantial investment made in equipment and training.

HDTV broadcasts in general and VSB modulation in particular are fascinating and lengthy topics that could fill entire books. Visit Zenith's web site at www.zenith.com for a comprehensive discussion on the subject. Ω

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